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16. Abstract

Ensuring that national air quality standards in Texas' two largest metropolitan areas are met has proven a difficult task for the Texas Natural Resource Conservation Commission (TNRCC) and other interested agencies. Tightening of emission budgets for these nonattainment areas results in consideration and adoption of inventive and controversial controls and restrictions. One such control recently adopted by TNRCC is that of postponing or shifting construction activities that require the use of heavy-duty diesel engines.

The purpose of this report is to review and assess the potential for emission reductions from nonroad diesel equipment using various control measures. This assessment compares the potential emission reduction benefits and cost of using emission control technologies to those of usage controls known as construction shifting. In general, the results of this study indicate that use of diesel engine emission control devices targeted to reduce oxides of nitrogen (NOx) emissions is more cost effective than the construction shift when measured in dollars per ton of NOx reduced. The cost of using diesel engine emission control technology is generally less than the cost of the construction shift and provides greater NOx emission reductions. The NOx reduction potential is greatest when diesel engine emission control devices are combined with the use of low-sulfur diesel fuel.

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POTENTIAL EMISSION REDUCTION EFFECTS OF ALTERNATIVE CONSTRUCTION EQUIPMENT CONTROL MEASURES

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FOREWORD

After the conclusion of this research work, a couple of regulatory changes occurred. First, the Texas Legislature passed SB 5 to create the Texas Emissions Reduction Plan, which becomes effective September 1, 2001. The legislation creates grants and other financial incentives for emissions reductions and removes the heavy-duty diesel equipment operating restrictions, affecting construction activities within the Dallas/Fort Worth (DFW) and Houston-Galveston (HG) nonattainment area State Implementation Plans (SIPs). The Texas Emissions Reduction Plan will be operated in part by Texas Natural Resource Conservation Commission (TNRCC). Specifically to this research, the Texas Emissions Reduction Plan establishes the Diesel Emissions Reduction Incentive Program that will offset the incremental costs of projects to reduce NOx emissions from construction equipment. The legislation caps the cost-effectiveness at $13,000 per ton NOx reduction.

There were additional changes made by TNRCC in the statewide Low Emission Diesel Fuel (LED) Program. TNRCC voted to change the implementation date from May 1, 2002, to April 1, 2005. Changes to this rule are not final and are currently gathering public comment. The changed rule also reduces the coverage area to 95 counties in East Texas. By moving the implementation date to April 1, 2005, Texas environmental rules become consistent with federal timelines. Implementation of the 15 parts per million (ppm) standard is scheduled for June 2006.

CHAPTER ONE – INTRODUCTION AND OVERVIEW

INTRODUCTION

Ensuring that national air quality standards in Texas' two largest metropolitan areas are met has proven a difficult task for TNRCC and other interested agencies. Tightening of emission budgets for these nonattainment areas results in consideration and adoption of inventive and controversial controls and restrictions. One such control recently adopted by TNRCC is that of postponing or shifting construction activities that require the use of heavy-duty diesel engines. Other control strategies targeting the construction sector include: implementation of LED; use of emission control devices; and accelerated purchase of clean nonroad highway diesel equipment.

The purpose of this report is to review and assess the potential for emission reductions from nonroad diesel equipment using various control measures. In addition, this assessment compares the potential emission reduction benefits and cost of emission control technologies to those of the adopted implementation of usage controls known as construction shifting.

Researchers began the assessment by reviewing diesel engine emission control devices targeted toward the nonroad sectors. Diesel emissions control is generally achieved by modifying the engine design, treating the exhaust (also referred to as after-treatment), modifying the fuel source, or a combination of these controls. Emission control technologies with available emission reduction cost and benefits show promise and are used to estimate the potential benefit and relative cost effectiveness for both DFW and HG regions. These technologies also estimate the same information for the construction shift adopted for both DFW and HG and compare it to the alternative strategies. The emission control technologies compared are typical exhaust after-treatments, fuels, and control techniques commercially available, some of which have published cost and emission benefits information. Construction shift emission benefits and costs information is limited to that provided in each region's Attainment Demonstration documents and the SIP.

It is important to note the emphasis for comparisons is on relative cost and emission benefits. The comparisons are used as sketch-planning tools to evaluate the various strategies for meeting air quality goals. Absolute costs and emissions reduction measurements of the various control measures would require more detailed analysis and research than presented within this report.

CONSTRUCTION SHIFT BACKGROUND

Atmospheric science indicates that the critical time for mixing oxides of nitrogen (NOx) and volatile organic compounds (VOC) to form ozone is in the early part of the day. The construction shift rule seeks to delay NOx production from construction equipment early in the day to reduce the amount of ozone produced during the afternoon in the presence of sunlight and hot temperatures.

The construction shift rule establishes a restriction on the use of heavy-duty diesel (HDD) construction equipment (≥50 Hp) during the ozone season beginning in 2005 for both the DFW and HG nonattainment areas[1]. The usage restriction in DFW will not allow designated construction equipment to operate between 6:00 a.m. and 10:00 a.m. from June 1 through October 31. In HG these equipment usage restrictions are in effect from 6:00 a.m. to noon throughout Daylight Savings Time[2].

The proposed rule establishes certain exemptions, including: operation of any heavy-duty construction equipment used exclusively for health and safety purposes (emergency operations) and equipment used in processing wet concrete. The rule may exempt operators who submit an alternative plan describing fleet modifications that will result in a reduction amount equivalent to this rule. To request an extension, operators must submit an alternative plan by May 31, 2002.

TNRCC analyzed emission credits from the construction equipment rule, assuming an uncontrolled fleet. A subsequent analysis using a controlled fleet on high-horsepower equipment, estimated the emissions credit results from Tier 2/Tier 3 implementation, using LED. Additional analysis broadened emissions credits by using only LED for a controlled fleet that included wider horsepower equipment ranges.

TNRCC estimates an aggregated 16 tons per day (TPD) of NOx reduction will result in DFW by implementing this rule and the Accelerated Purchase rule (*1*: Page 6-13). However,

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[1] The DFW nonattainment area currently includes Dallas, Tarrant, Collin, and Denton counties. The HG nonattainment area includes Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, and Waller counties.

[2] First weekend in April through the last weekend in October.

they did not state the exact benefit. In HG, 8 TPD are expected to shift, producing an equivalent 6.7 TPD NOx reduction (2: Page 6-3).

The *Dallas-Ft Worth Attainment Demonstration*, an April 2000 document (*1*) states that TNRCC does not anticipate significant economic impact on affected agencies and businesses beyond the shift in work schedule because the proposed strategy does not require additional control equipment or new technology. TNRCC acknowledges that the proposed rule "may require" adjustments to work schedules and could cause extensions of construction timelines. According to the *DFW Attainment Demonstration* document, these effects "may have significant fiscal implications in an amount that cannot be determined at this time" (*1*: Page 6-12). The fiscal impacts depend on the "scope...and time-critical nature" of the project (*1*: Page 6-12). TNRCC's preliminary cost estimate provided within the *HG Attainment Demonstration* document reports that an estimated 15 to 20 percent cost increase would result in an additional $70 to 93 million annually in TxDOT-related construction costs in HG (2: Page 6-8).

As indicated in the *DFW Attainment Demonstration* document (*1*: Page 2-4), 1996 NOx emissions for DFW totaled 581.3 TPD. *Improved Construction Inventory Documentation,* Appendix V of the *DFW Attainment Demonstration* document (*3*), states that the construction industry as a whole contributes 50.3 TPD (1996 NONROAD Run) to this inventory. This contribution equates to a little less than 10 percent of the total NOx inventory. The construction industry represents 37 percent of the area/nonroad inventory (50.3 TPD of 132.9 TPD). The heavy-highway sector represents approximately 4 percent of the area/nonroad inventory total and 1 percent of the total NOx inventory. Researchers derived these approximations from information provided by TNRCC staff in which they stated that highway activity represented 11.5 percent of the construction emissions[3]. Figures 1 and 2 (pages 31 and 32) provide additional comparisons for HG and DFW, respectively.

When comparing the preliminary emission reduction estimate of 16 TPD provided by TNRCC (*1*: Page 6-13) to the construction industry inventory, researchers expect a significant 32 percent reduction (*16* TPD of 50.3 TPD) from the construction industry through the implementation of both the construction shift and accelerated purchase. Using the ratio of

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[3] Personal correspondence from Jim MacKay, TNRCC. October 6, 2000.

construction shift benefits to accelerated purchase of Tier 2/Tier 3 equipment benefits from Houston (39 percent), the construction shift in DFW should produce a 12 percent reduction in daily construction sector emissions.

The development of sector emissions through to the photochemical modeling is as much art as it is science. Numerous assumptions must be made to generate and distribute emission sources and determine the impacts or effectiveness of proposed control strategies. The proposed policy will attempt to control 3-14 percent of a region's NOx contributions to yield an overall reduction of several tons. TNRCC has neither developed specific estimates nor itemized the emissions reduced resulting from this policy in DFW. Instead, the preliminary reduction estimate of 16 TPD cited in the *DFW Attainment Demonstration* is tied to another policy: accelerated purchase.

The possible delayed completion of public works projects due to the implementation of the construction shift rule is an issue for consideration. Whether these projects are transportation, wastewater, public water supply, or other important and/or critical projects, the construction shift rule will likely have an impact on the construction industry and the public, as well as air quality.

CHAPTER TWO – NONROAD DIESEL EMISSION CONTROL

DIESEL ENGINE EMISSION CONTROL

The chapter presents a review of emission control technologies, associated costs, and potential emission reductions. The report limits examination to two broad categories of technological control measures for nonroad diesel applications: engine emission control devices and fuels.

The primary sources for information on diesel emission control devices and fuel are the United States Environmental Protection Agency (EPA), California Air Resources Board (CARB) and the Manufacturers of Emission Control Association (MECA). Researchers used the following in particular: EPA's May 2000 *Draft Regulatory Impact Analysis for the Proposed Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements Rule* (4); CARB's October 2000 report by the Stationary Source Division and Mobile Source Control Division entitled *Risk Reduction Plan to Reduce PM Emission from Diesel-Fueled Engines and Vehicles* (5); and the MECA March 2000 report: *Emission Control Retrofit of Diesel Fuel Vehicle* (6).

Diesel emissions control can be achieved by:

- modifying the engine design,
- treating the exhaust (also referred to as after-treatment),
- modifying the fuel source, or a combination of these controls.

The following section will briefly review after-treatment, engine modification, and fuel as means to reduce diesel emissions. The review is limited to current regulatory strategies.

Retrofit Controls and Diesel Exhaust After-Treatment

Diesel exhaust after-treatment devices include diesel traps or filters and diesel catalysts. Diesel traps, which are primarily diesel filters, control diesel particulate matter (DPM) emissions by physically trapping the particulates, usually through a porous medium. The major challenge in the design and use of diesel filter systems is regenerating the filter's trap in a reliable and cost-effective manner.

DPM is a complex aggregate of solid and liquid material generally classified into three fractions:

1. the inorganic/solid fraction (soot);
2. the organic fraction, often referred to as a soluble organic fraction (SOF); and
3. the sulfate (SO_4) fraction (hydrated sulfuric acid).

The composition of these sub-micron size particles in diesel exhaust varies depending on engine load and usage conditions.

Diesel catalysts control emissions by promoting oxidation processes in the exhaust gas similar to those in catalytic converters used in automobiles. Diesel oxidation catalysts (DOCs) most effectively reduce the SOF of diesel particulates, gas-phase hydrocarbons (HC), and carbon monoxide (CO). DOCs are used commercially for many over-the-road and off-highway applications. Some retrofit emission control systems use a combination of DOCs, filters, air enhancement, and engine adjustments for emission reduction. Diesel filters and DOCs alone have little effect on NOx emissions.

Diesel Particulate Filters and Traps

Diesel particulate filters positioned in the exhaust stream capture particulates as the exhaust passes through the exhaust system. As expected, the volume of particulates trapped from diesel exhaust is sufficient to clog most filters over time. Therefore, filter systems need a means to dispose of trapped particulates, or to regenerate the filter. One method of regeneration is through burning or oxidizing the particulates. Another method used primarily in nonroad applications is to size the filter to collect enough particulates to be effective for a working shift and to replace it regularly (*6*).

Most commercial filter materials in use include ceramic monoliths, fiber-wound cartridges, silica carbide, and temperature resistant paper for disposable filters. The particulate matter (PM) efficiency for these types of filters ranges from 50 percent to 90 percent. The challenge lies in the regeneration of the filters. The relatively low temperature of diesel exhaust is inadequate to allow a catalyst to work effectively. Therefore, regeneration methods include the use of fuel-borne catalysts to raise ignition temperatures, fuel burners to heat exhaust, and, more commonly, catalyst coatings on the filter element (6).

According to MECA, filter system costs range from $10 to $20 per horsepower (hp) depending on the application and conditions of use. Per-vehicle costs range from approximately $600 to $2,000 and also depend on the technology and application in use. Diesel particulate filter systems use began in the mid-1980s (7).

Diesel Oxidation Catalyst

DOCs are the leading retrofit control strategy to reduce PM, CO, and HC emissions for both nonroad and onroad diesel applications, and have been in use for more than 20 years (6). Modern catalytic converters consist of honeycomb substrate coated with metal (e.g., platinum or paladium) catalyst packaged in a stainless steel container. The honeycomb structure uses many small channels and acres of high catalytic contact area to exhaust gases. As the hot gases contact the catalyst, oxidation converts several exhaust pollutants into harmless substances: carbon dioxide (CO_2) and water (H_2O).

The DOC oxidizes CO, gas phase HC, and the SOF fraction of diesel particulate matter to CO_2 and H_2O. The catalyst activity increases with temperature, and the percentage of SOF influences the level of particulate reduction. The sulfur content of diesel fuel is critical to catalysts. The lower the sulfur content in the fuel, the more effective oxidation catalysts can become. Retrofits for vehicles are effective on vehicles using greater than 0.05 percent sulfur fuel and typical nonroad retrofit applications reduce PM, HC, and CO emissions for fuel containing 0.25 percent weight sulfur. The performance of an oxidation catalyst using an elevated fuel sulfur level can vary greatly depending on the catalyst formulation, engine type, and duty cycle (6).

Most DOCs are used in mining equipment and material handling (forklifts) equipment. The underground mining and material handling industries have installed over 250,000 catalysts; the urban bus retrofit program has installed more than 10,000 oxidation catalysts; and over 1,000 systems have been retrofitted to highway trucks. DOC-equipped engines fueled with low-sulfur diesel (levels at or below 0.05 percent sulfur) have achieved PM reductions of 20 to 50 percent, as well as 60 to 90 percent reductions for both HC (including those HC species considered toxic), and CO. A Society of Automotive Engineers (SAE) technical paper indicated DOCs were capable of reducing the SOF fraction of particulates by 90 percent and reducing total PM by 40 to 50 percent under certain conditions (7). DOCs have minimal effect on reducing NOx.

Based on reported experience from the EPA urban bus retrofit program, life cycle costs of DOCs are less than $2,300 per bus. Due to the wide range of horsepower ratings for equipment used in nonroad applications, the cost variation is greater. The cost for small in-line muffler replacements ranges from $300 to $600 per unit ($1.00 to $2.00 per hp) to several thousand dollars for large units on large nonroad vehicles (6).

Catalyst-Based Filters

CARB evaluated various types of diesel emission control technologies and found that the most effective control technologies were catalyst-based diesel particulate filters (catalyst-based DPFs) that include filter catalysts. Catalyst-based filters use catalyst materials to reduce the temperature at which collected diesel PM oxidizes. The catalyst material can be directly incorporated into the filter system or added to the fuel as a fuel-borne catalyst (FBC). Although catalyst-based filters can function with diesel fuels of varying sulfur content, the greatest reductions come from using very low-sulfur fuels. Used with very low-sulfur (<15 ppm by weight sulfur) diesel fuel, catalyst-based filters can reduce diesel PM emissions by over 85 percent (5).

Table 1 presents the range of control efficiency for catalyst-based filters and new diesel-fueled engines. Based on available test information summarized from CARB's technology review, the control efficiency information ranges from 85 to 90 percent for catalyst-based filters. Effectiveness of catalyst-based filters is demonstrated in Europe on more than 6,500 buses and heavy-duty trucks and on a much more limited basis in the United States, particularly in California and New York.

Table 1. Control Technology Efficiencies.

Control Technology	Diesel PM Control percent	Efficiency Description
Catalyst-Based DPFs /Very low-sulfur fuel	85 - 97	Particulate filter system where the catalyst material is either incorporated into the filter or added to the fuel; Diesel fuel with sulfur content < 15 ppm.
New Engine	Up to 85	Replaces existing engines with engines certified to meet CARB/U.S. EPA off-road engine emission standards.

Source: Table 1 from CARB Risk Reduction Plan, October 2000 (*6*)

Tables 2 and 3 list the costs of control technologies under different types of use. The cost data from CARB are consistent with data from MECA that indicate a range of $30 to $50 per horsepower (*6*). EPA reported the cost for light heavy-duty diesel (LHDD) engines at $634, medium heavy-duty diesel (MHDD) at $796, and heavy heavy-duty diesel (HHDD) duty engines at $1,029; these estimates are consistent with other estimates. It is important to note that retrofit costs are four to five times higher than costs for new engine modification.

Table 2. Retrofit Costs for Catalyst-Based Filters.

Technology	40 hp	100hp	400 hp	1400 hp
Capital Cost	$1,300-$5,000	$2,000-$7,500	$7,000-$10,000	$30,000-$44,000

Source: Table 2 from CARB Risk Reduction Plan, October 2000 (*6*)

Table 3. Retrofit Costs for Off-Road Catalyst-Based Filters.

Technology	190 hp	275 hp	475 hp
Catalyst-based DPF	$5,700-$9,500	$8,250-$13,750	$13,500-$23,750

Sources: Table 1, Table 2, and Table 3 from CARB Risk Reduction Plan to Reduce PM Emission from Diesel-Fueled Engines and Vehicles, Stationary Source Division, Mobile Source Control Division, October 2000. Some catalyst-based technologies require low-sulfur fuel. The incremental cost of this fuel is projected to be less than $0.05 per gallon

NOx TARGETED TECHNOLOGIES

Whereas catalyst-based filters and traps are effective in reducing diesel particulates, the technologies reviewed below aim toward reducing NOx emissions.

Selective Catalytic Reduction

Unlike most stand-alone filter-based applications, the technology known as selective catalytic reduction (SCR) effectively reduces NOx. SCR introduces urea as a reducing agent ahead of the catalyst to provide reductions of NOx (75 to 90 percent), HC (50 to 90 percent), and PM (30 to 50 percent)(*7*). SCR use is more prevalent among higher horsepower diesel engines such as marine vessels, locomotives, and fixed sources such as boilers and power plants. However, demonstration projects have used SCR for lower horsepower trucks and buses.

According to TNRCC, Siemens Westinghouse SCR is designed for engines greater than 175 horsepower, and assumes SCR could be implemented on 80 percent of such nonroad sources *2*). However, the modal horsepower range for HG is 100-175 horsepower, which could limit the use of SCR for construction equipment at this time. Alternatively, the NOxTECH, Inc. SCR system is available for lower horsepower ranges.

The cost of SCR is difficult to determine according to MECA because it is a relatively new application for trucks, buses, and lower horsepower ranges. The cost for retrofitting nonroad construction specifically is unavailable, but a 1997 study (*8*) reported the effectiveness of SCR as $1,100 per ton NOx reduced based on limited testing.

The NOxTECH Emission Control System by NOxTECH, Inc., is used on stationary diesel engine generators. The manufacturer reports the initial costs are $52 to $75 per horsepower for installations requiring urea injection and heat exchanger. Urea costs estimates are at $300 per ton of NOx reduced with a fuel efficiency penalty of 5 to 8 percent.

Based on a stationary engine, the SINOX SCR system by Siemens Westinghouse Power Corporation, reports an initial cost of $7,000 for a 367 hp engine ($19 per hp) with similar urea and fuel penalty costs (*6*: Appendix IX, Page ix-11). Among NOx emission control devices reviewed, the SCR technology is among few commercially available at this time demonstrating NOx reduction results.

Lean NOx Catalysts

Two types of lean NOx catalysts (active and passive) have been under development, but neither is commercially available. Active lean NOx catalysts inject a reductant upstream to reduce NOx to N_2 and O_2. Active lean NOx catalysts have demonstrated up to 30 percent reduction of NOx under limited steady state conditions, but there is a 7 percent fuel economy penalty. Additionally, NOx reductions over the heavy-duty transient federal test protocol (FTP) are approximately 12 percent because of the excedance of optimum NOx reduction efficiency range (*4*).

The passive lean NOx catalysts washcoat incorporates a zeolite to adsorb HCs from the exhaust stream. Passive lean NOx catalysts are capable of steady state NOx reductions of less than 10 percent. EPA views neither active nor passive lean NOx catalysts as favorable technologies for NOx reduction technologies without major improvements (*4*). Both types of lean NOx catalysts require low-sulfur diesel fuel because zeolite catalysts are sulfur intolerant.

NOx Adsorbers

The application of NOx adsorbers to diesel engines is relatively new. The power generation industry began using NOx adsorbers on stationary sources less than five years ago. Recent applications include the use of lean-burn gasoline engine NOx control. The NOx adsorbers consist of a an oxidation catalyst (e.g., platinum), an alkaline earth metal to store NOx (e.g., barium), a NOx reduction catalyst (e.g., rhodium), and a container substrate to hold the catalyst wash support. Unlike catalysts, NOx adsorbers store NOx under lean conditions and release and catalytically reduce the stored NOx under rich conditions. The NOx adsorbers are periodically regenerated using reductants such as CO or HCs in the diesel fuel (*4*).

The cost for NOx adsorbers is estimated to range from $890 to $1,410 depending on the application (*4*). EPA reported the cost for LHDD at $890, MHDD at $1,047, and HHDD at $1,410. It is important to note that retrofit costs are four to five times higher than costs for new engine modification (*4*). The greatest challenge to NOx adsorbers' effectiveness is the adverse affect of sulfur content in fuel. Nonetheless, EPA looks favorably toward NOx adsorbers as the most effective technology to achieve new NOx standards when used with low-sulfur fuels, since

NOx adsorbers can provide NOx conversions in excess of 90 percent over a wide range of temperatures.

Air Enhancement Technology

Air enhancement technologies such as electronic superchargers have demonstrated simultaneous reductions of PM (20 to 40 percent), CO (30 to 65 percent), and visible smoke (25 to 90 percent). These systems can improve vehicle performance without reducing fuel efficiency and have gained a "universal exemption" by CARB for heavy-duty mechanical unit injection (MUI) diesel engines. The technology has been used in transit buses, line haulers, and water tankers in the U.S. and worldwide.

The cost of air enhancement technologies varies depending on horsepower and airflow requirements. However, MECA reports medium and heavy-duty applications range from $3,000 to $5,000 with some manufacturers aiming for costs of $1,500 to $2,000 (*8*).

COMBINATION TECHNOLOGIES

In many instances, combining technologies and engine modifications, as well as control technologies and low-sulfur fuel, results in diesel emission reductions. This is particularly true for NOx emissions. Engine modifications may include the use of injection timing retard or exhaust gas recirculation (EGR). MECA summarizes the following combinations (*6*: Page 20):

- A combination of DOCs, DPM filters, air enhancement, and engine modifications used for emission reduction. One system using ceramic coatings [zeolites] with fuel injection retardants and an oxidation catalyst demonstrated a 40 percent NOx reduction and maintained low particulate emissions.
- Thermal management technologies combine the use of catalysts with lean-NOx fuel to achieve reductions in PM, CO, HC, and NOx.
- Substantial PM emission reductions using a proprietary camshaft modification in combination with oxidation catalysts.

Engine Modifications

Engine modifications encompass both retrofit and new engine purchases. Retrofit engine modifications involve rebuilds to integrate changes in timing, fuel injection, exhaust, or other components to retrofit diesel engines. Several engine modifications and design changes proposed to control emission include stand-alone modifications as well as those used in conjunction with after-treatment and/or fuel changes.

Exhaust Gas Recirculation (EGR)

EGR involves mixing exhaust gas with intake air - a technology that has been used in gasoline automobiles. A test by MECA and the Southwest Research Institute used EGR combined with an oxidation catalyst to achieve a NOx + HC emission of less than 2.5 g/bhp-hr (6). EGR's estimated cost is $600 per unit (not including installation) with potential NOx reduction cost of approximately $44 per ton (6).

Injection Timing Retard

Injection timing retard involves the use of electronic controls and software codes to improve fuel injection systems and produce more efficient combustion. NOx reductions of up to 40 percent were achieved in onroad vehicles using injection-timing retard. EPA's urban bus retrofit program has approved this technology.

Cam Shaft Cylinder Reengineering Kit

The camshaft cylinder reengineering kit consists of specific engine retrofit components including a proprietary camshaft. It reduces NOx by increasing the volume of exhaust gas remaining in the combustion chamber after the power stroke. The exhaust gas remaining in the chamber absorbs heat and reduces combustion temperature thereby lowering NOx emissions. The technology is certified by CARB. The manufacturer indicates no greater than 1.0 g/bhp-hr HC, 8.5 g/bhp-hr CO, 5.8 g/bhp-hr NOx, and 0.16 g/bhp-hr PM. The product is commercially available with a cost of $3,480 to $15,680 depending on horsepower. The CARB technology review identified engine retrofits that ranged in price from $1,500 to $3,000 for smaller light duty engines and up to $15,000 for high horsepower engines (5).

MECA SUMMARY AND CONCLUSIONS

The MECA report *Emission Control Retrofit of Diesel-Fueled Vehicles* offered the following conclusions based on its review of emission controls for diesel-fueled engines (6: Page 20):

- Oxidation catalyst technology can substantially reduce particulate, HC, smoke, and odor from diesel engines, and improvements in oxidation catalyst technology continue to evolve to further enhance the application of this technology to diesel engines.
- SCR can simultaneously reduce NOx, PM, and HC.
- Filter technology can reduce harmful particulate emissions by up to 90 percent or more, as well as substantially reduce smoke.
- Air enhancement technologies can be used to reduce emissions of PM, CO, and smoke. They can also be used to enhance the performance of other retrofit controls such as oxidation catalysts.
- Thermal management technologies combined with catalyst technology, including lean-NOx catalyst technology, can be used to simultaneously reduce PM, CO, HC, and NOx.
- Both oxidation catalysts and filters can be used in conjunction with engine management techniques, e.g., injection timing retard or EGR, to reduce diesel particulate CO, HC, and NOx emissions.
- Several oxidation catalysts systems have been approved under U.S. EPA's urban bus rebuild/retrofit program along with three 0.1 g/bhp-hr systems. Another 0.1 g/bhp-hr system has been submitted for certification approval.
- For oxidation catalyst retrofit applications, fuel sulfur levels below 0.05 percent wt are desirable, but not required. Lower fuel sulfur levels increases the PM reductions provided and makes vehicle integration simpler.
- When selecting a retrofit control technology, it is important to ensure that the technology is compatible with the duty cycle of the vehicle, the available fuels, and the desired emissions reductions.

DIESEL FUEL

Both EPA and TNRCC recognize reducing the sulfur content in diesel fuel as an important strategy for reducing future diesel engine emissions. Achieving effective emission control technologies for diesel engines requires low-sulfur fuel.. Federal requirements for new diesel engine emission standards that take effect in 2007 and low-sulfur fuel requirements that take effect in 2006 will combine to effectively reduce NOx and nonmethane HC emissions. TNRCC will begin implementing its requirements for low sulfur-fuel in 2002. Additionally, TNRCC requirements will encompass both onroad and nonroad engines.

TNRCC's approach to reformulating diesel fuel to benefit air quality involves reducing the sulfur and aromatic HC content, and increasing cetane content. Reduction of sulfur in diesel fuels serves to enable new engine and after-treatment technologies that are sensitive to sulfur compounds in exhaust.

Texas Low Emission Diesel (LED) Fuel Program

TNRCC has initiated a program to implement LED fuels. The LED Program begins April 1, 2005, and requires that, beginning on that date, diesel fuel produced for delivery and ultimate sale to the consumer in affected areas shall not exceed 500 ppm sulfur, must contain less than 10 percent by volume of aromatic hydrocarbons, and must have a cetane number of 48 or greater. The LED Program requires that LED fuel be used year-round in all diesel-fueled compression-ignition engines in both onroad vehicles and nonroad equipment operating within the affected counties. In addition, these rules will require the diesel fuel supplied to the DFW, Beaumont Port Arthur (BPA), and HG ozone nonattainment areas and 95 central and eastern Texas counties reduce the sulfur content to 15 ppm beginning June 1, 2006. The rule also requires diesel fuel producers and importers who provide fuel to the affected areas to register with the commission and provide quarterly status reports. The new rule applies directly to the supplier of the fuel, not the user, in order to regulate the fuel available for purchase in the state.

LED rules will require fuel for both onroad and nonroad use in:

- eight counties in the HG region including Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, and Waller;
- four counties for the DFW region, including Collin, Dallas, Denton, and Tarrant;

- three counties of the BPA region ncluding Hardin, Jefferson, and Orange; and
- 95 additional central and eastern Texas counties including Anderson, Angelina, Aransas, Atascosa, Austin, Bastrop, Bee, Bell, Bexar, Bosque, Bowie, Brazos, Burleson, Caldwell, Calhoun, Camp, Cass, Cherokee, Colorado, Comal, Cooke, Coryell, De Witt, Delta, Ellis, Falls, Fannin, Fayette, Franklin, Freestone, Goliad, Gonzales, Grayson, Gregg, Grimes, Guadalupe, Harrison, Hays, Henderson, Hill, Hood, Hopkins, Houston, Hunt, Jackson, Jasper, Johnson, Karnes, Kaufman, Lamar, Lavaca, Lee, Leon, Limestone, Live Oak, Madison, Marion, Matagorda, McLennan, Milam, Morris, Nacogdoches, Navarro, Newton, Nueces, Panola, Parker, Polk, Rains, Red River, Refugio, Robertson, Rockwall, Rusk, Sabine, San Jacinto, San Patricio, San Augustine, Shelby, Smith, Somervell, Titus, Travis, Trinity, Tyler, Upshur, Van Zandt, Victoria, Walker, Washington, Wharton, Williamson, Wilson, Wise, and Wood.

Effects of LED

In a literature review, Lee, Pedley, and Hobbs (7) studied the fuel quality effects on NOx and PM diesel emissions. In general, they reported:

- Reducing sulfur from 0.30 percent (3000 ppm) to 0.05 percent (500 ppm) yields large benefits for PM but little or no effect on NOx, HC, or CO.
- Reducing sulfur content below 0.05 percent (500 ppm) yields minimal benefits, but low sulfur content is necessary as an enabler of after-treatment technology to reduce NOx and HC.
- Increasing cetane yields small benefit in NOx, and variable to no effect on PM.
- Large decreases in aromatics (from 10 percent to 30 percent) give small reductions (0 to 5 percent) in NOx; it has no effect on PM, HC, or CO.
- Reducing poly-aromatic HCs yields a small benefit in HC and NOx emissions, and large PM benefits for high emission engines, but it has no effect on low emission engines.

The TNRCC has countered some industry skeptics of potential NOx benefits from modifying cetane and aromatic HC concentrations in reformulated diesel fuel by referencing their own study by the Eastern Research Group, Inc. (ERG) (9), and their participation in EPA's heavy-duty engine working group (HDEWG). TNRCC claims reductions of 7 percent statewide are indeed reasonable and conservative. According to TNRCC, the 7 percent NOx emission reduction value is only slightly higher than the 5.7 percent figure used for electronically controlled engines reported in the ERG analysis.

In supporting their claim, the TNRCC referenced the SAE paper (7) by citing a less than 5 percent impact for total aromatic reductions from 30 percent to 10 percent by weight stating that on a percent basis, poly-aromatics should contribute more to NOx than a corresponding amount of mono-aromatics. Furthermore, if poly-aromatics are reduced disproportionately compared to mono-aromatics, total aromatic reductions could be even greater. Since the HDEWG predictive model accounts for both poly- and mono-aromatic levels, TNRCC claims that the modeled result of 5.7 percent is within the range of reasonable reductions (9).

TNRCC estimates that a 7 percent reduction in NOx can be achieved by 2007 with the LED Program and estimates a 30 TPD reduction in NOx statewide, 6.84 TPD attributable to HG. CARB claims a higher potential emission reduction (about 12 percent) than TNRCC for electronically controlled diesel engines using an equivalent fuel specification. TNRCC bases NOx benefits on testing under the HDEWG, utilizing a sophisticated fuel matrix and exhaust gas recirculation representative of engines meeting the upcoming 2004 standards (9).

Although reformulated diesel fuels alone may have a limited effect on NOx emissions, low-sulfur diesel fuels in combination with various control technologies can yield significant emission benefits. A MECA study demonstrated the enabler effect of low-sulfur fuels. The study used two low-sulfur fuels, 384 ppm sulfur diesel and 54 ppm sulfur diesel, in combination with DOCs, DPFs, and SCRs. The study demonstrated that PM emissions of 0.03 g/bhp-hr combined with NOx+HC emissions of 1.5 g/bhp-hr could be achieved (10).

Diesel Fuel Costs

Identifying low-sulfur diesel fuel price projections is challenging in light of competing interests, changing technologies, and fluctuating fuel prices in general. For the purposes of this report, researchers present the range of prices so that a broad comparison can be made. Just as emission control equipment prices vary, so do fuel price projections.

Predictions on the cost increase for low-sulfur fuels (<500 ppm) vary from $0.04 to $0.14 per gallon depending on the source. The TNRCC reports production cost of $0.04 to $0.08 per gallon of diesel fuel to comply with the new rules. Industry sources say retail cost increases will range from $0.10 to $0.14 per gallon. For very low-sulfur fuel, with sulfur content of less than 15 ppm required by 2006, some sources estimate an additional $0.05 to $0.19 per gallon increase. Potential implementation of desulfation processes at fuel refineries may also affect future price.

In its regulatory impact analysis, the EPA reports that low-sulfur diesel fuel cost will increase $0.044 per gallon, and per-vehicle costs adjusted to net present value (NPV) range from $3,704 for heavy-duty vehicles to $536 for light-heavy duty vehicles. A detailed cost analysis is available in EPA420-F-00-022 (*4*: Ch. V).

Alternative Diesel Fuels

Several diesel formulations and diesel emulsions have demonstrated emission benefits including: Swedish Urban Diesel, ARCO's Emission Control Diesel (EC-D), Synthetic Diesel, and two diesel emulsion products. The list below summarizes these fuels (*5*):

- ARCO's EC-D is a very low sulfur, low aromatic, and high cetane diesel fuel produced from typical crude oil. Preliminary tests indicate a 10-15 percent NOx reduction for buses and 11 percent and 3 percent for trucks.
- The Fischer-Tropsch gas to liquid (GTL) conversion process refines ultra-low-aromatic synthetic diesel fuels. Preliminary tests compared to CARB fuel resulted in a 4 percent reduction in NOx, 36 percent reduction in HC, 20 percent reduction in CO, and 26 percent reduction in PM.
- Fuel water emulsions from A-55 Incorporated and Lubrizol Corporation have demonstrated emission benefits. A-55 has a patented a diesel/water emulsion and a naptha/water emulsion. The presence of water, which lowers combustion temperatures, reduces both diesel PM and NOx emissions. Preliminary tests on A-55 fuel in transit buses showed NOx reductions of 54 percent and diesel PM reductions

of 20 percent (*4*). The Lubrizol fuel, called PuriNOX™, is a diesel/water emulsion with reported NOx reductions of 15 percent and PM reductions of 51 percent. Other diesel emulsions under development include ethanol/diesel micro emulsions.

- Dimethyl ether (DME) is made from fossil feedstocks including natural gas, coal, and some renewable feedstocks. When used as fuel for diesel engines, DME offers potential NOx and PM emissions benefits.

CARB Summary Table

CARB evaluated a range of emission control technologies and published the results in "Risk Reduction Plan to Reduce PM Emission from Diesel-Fueled Engines and Vehicles" (*5*). This listing of control technologies evaluated by CARB appears in Table 4. Details of the evaluations are available in Appendix IX of the CARB report (*5*). Tables 5 and 6 on the following pages present a summary of the cost and emission reduction potential of emission technologies selected from the CARB evaluation.

Table 4. Diesel Emission Controls Technologies Reviewed by CARB.

Control Technology	Product
Alternative Fuels	Biodiesel, various manufacturers Fumigation Natural Gas/Diesel Bi-Fuel Retrofit Kit, Innovative Technologies Group
Engine Design and Modifications	Cam Shaft Cylinder Reengineering Kit, Clean Cam Technology Systems Diesel Emission Control System, Clean Air Technology 3. ECOTIP Superstack Fuel Injectors, Interstate Diesel IET 2000 Series Emission/Fuel Reduction System, International Engine Technologies, Ltd.
Fuel-Borne Catalysts	COMTEC Emission Control Device, COMTEC Combustion Technologies, Inc. Platinum Plus® DFX diesel fuel combustion catalyst, Clean Diesel Technologies, Inc.
Other Exhaust Treatment Technologies	NOxTECH Emission Control System, NOxTECH, Inc. SINOx (SCR type system) System, Siemens Westinghouse Power Corporation
Oxidation/Oxidation Catalysts	CEM Catalytic Exhaust Muffler, Johnson Matthey CleanDIESEL Converters, Clean Air Systems DCC Diesel Catalytic Converter, Johnson Matthey Dieselytic SX Exhaust Gas Purifier, Catalytic Exhaust Products Ltd. Flameless Thermal Oxidizer, Thermatrix, Inc. Nett D-series Diesel Purifier, Nett Technologies Nett Standard Diesel Purifier, Nett Technologies PTX Oxidation Catalyst, Engelhard Corporation
Particulate Filters	3M Diesel Particulate Filter Cartridges, Minnesota Mining and Manufacturing (3M) CleanDIESEL Soot Filter, Clean Air Systems Combifilter, Engine Control Systems CRT Particulate Filter, Johnson Matthey DPX Particulate Filter, Engelhard Corporation
	QuadCat Four-Way Catalytic Converter, Ceryx, Inc. "Trap-Muffler" System, Doubletree Technologies, Inc. Nett SF Soot Filter, Nett Technologies, Inc.

Table 5. Summary of Particulate Emission Control Cost and Reduction Efficiencies

Control Technology Category	Emission Reduction Effectiveness (percent)				Cost Information
	PM	HC	CO	NOx	
PM Targeted After-treatments					
Filter / Traps	50-90	50-90	40-90	<1	$10 to $20 per hp, $625 to $2250 per vehicle
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Ex. Clean Diesel Tech. Platinum Plus FBC+DPF (350 ppm sulfur fuel + fuel-borne catalyst)	96	66	42	0	
Catalyst-based filters (500 ppm sulfur fuel)	70-90	30-90	30-90	<5	$10 to $20 per hp + overhead and maintenance (O&M)
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Ex. Johnson Matthey	93	86	90	2	--- --
Ex. QuadCat by Ceryx w/ NOx catalyst	90	90	90	30-50	NA $5 to $10K up to 400 hp
Diesel Oxidation Catalyst DOC (500 ppm sulfur)	20-50	60-90	60-90	<5	$4 to $30 per hp + O&M, annualized cost for 100 hp $200 to $990, for 275 hp $420 to $1,210
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Ex. Nett D-Series	10-50	60-86	80	<1	$4 to $20 per hp

Table 6. Summary of NOx After-Treatments Cost and Reduction Efficiencies.

Control Technology Category	Emission Reduction Effectiveness (percent)				Cost Information
	PM	HC	CO	NOx	
NOx Targeted After-treatment					
SCR (500 ppm sulfur fuel)	30-50	50-90t	40-90	75-90	$50 to $70 per hp + urea cost + O&M
Ex SINOx SCR by Siemens Westinghouse	20-50	60-90	40-90	65-85	$50 to $60 per hp + $300 per ton NOx reduced urea + $715 to $1500 per year O&M + fuel penalty; annualized cost for 275 hp = $2,940 to $4,070
Ex. NOxTECH Inc.	50-90	NA	50-90	90-95	$52 to $75 per hp + $300 per ton NOx reduced urea + O&M + fuel penalty; annualized cost for 275 hp = $2,460 to $4,460; for 100 hp = $1370 to $3050
Lean NOx Catalysts (15 ppm sulfur)	90	NA	NA	30	Cost per hp NA, fuel penalty 7 to 12 percent
NOx Adsorbers (15 ppm fuel)	NA	NA	NA	50-90	$890 for MHDD to $1410 for HHDD per vehicle

NA : not available

CHAPTER THREE – CONTROL MEASURE COMPARISON

The chapter develops and presents estimates of the relative cost and benefits for two control measures. First the cost and emission benefits of using the construction shift for both HG and DFW are estimated. Next, the cost and emission benefits of using emission control technology are estimated. The chapter then presents a comparison of the two control measures.

CONSTRUCTION SHIFT ESTIMATE METHODOLOGY

Researchers interviewed several staff members of the TNRCC regarding the processes used to develop and estimate construction equipment emissions, taking a top-down approach. The interview process began at the photochemical modeling level, advanced to the emission inventory input development, and culminated in the nonroad mobile source inventory development specifically targeting the construction equipment sector. Researchers supplemented interviews with an extensive review of several publicly available TNRCC documents detailing the development and application of locally developed construction equipment inventories and associated emission estimates.

The following is a summary of the interview findings with TNRCC staff, and estimates of highway construction emissions.

TNRCC Staff Interviews

During July 2000, TTI researchers interviewed several TNRCC staff in the Office of Environmental Policy, Analysis, and Assessment's Technical Analysis Division using both telephone and personal interview methods. Interviews were first conducted at the photochemical modeling level and progressed toward the development of the construction equipment inventories and activities.

Photochemical Modeling

The emission effects of the highway construction sector cannot be determined at the photochemical modeling level of analysis[4]. This complex model, combining gross emission inventories (tons) and source locations with meteorology, cannot distinguish between specific groups of sub-sources.

The photochemical model strictly replicates the day and hour of model events. Model event dates for DFW are June 21-22, 1995 (plus two "ramp-up" days), and July 3, 1996 (plus three "ramp-up" days). Model event dates for HG are September 8-11, 1993 (plus two "ramp-up" days). The nonroad emissions source is typically treated as an area source.

Emission Inventory Compilation

The emission inventory group[5] prepares the inputs for the photochemical model. At this point in the process, the emission inventory group compiles all the sources into their respective classes and distributes them within the grid system of the photochemical model. Because only total construction sector emissions were provided, this group could not differentiate between sources of construction emissions.

Spatial allocation of emissions within the photochemical model is more an art than a science. Land areas received allocation of construction emissions based on USGS data classifying them as industrial, residential, or commercial. Travel demand model and vehicle-miles traveled (VMT) projections guided the distribution of heavy-highway sector emission sources among the regional analysis zones (RAZ). Within HG, this distribution represented approximately 200 RAZ. The area of a RAZ can vary considerably, posing challenges to TNRCC staff. Because the population, employment, and population growth data contained in the TDM are reliable, RAZ was used to allocate heavy-highway sector. This process may undercount heavy-highway sector contributions from the rural areas. According to TNRCC, "using 1993 surrogates for 2007 emissions may artificially concentrate the emissions into the

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[4] Telephone interview with Pete Breitenbach, TNRCC. July 10, 2000.

[5] Personal interview with Jim Smith, TNRCC. July 13, 2000.

former urban area, which can in turn affect the model's future ozone forecasts (2)." Population, employment, and growth in each RAZ from 2006-2008 forecasted the 2007 construction activity.

TNRCC staff and construction industry experts reviewed emissions allocations and found them to be reasonable. Staff observed that 70 percent of the construction activity in HG was located in Harris County. The location of heavy-highway sector emissions also appeared reasonable to staff and outside experts.

At the time of the interviews, TNRCC staff remarked that municipal and heavy-highway sectors represented 30 and 20 percent of the construction emissions, respectively. In later correspondence, TNRCC staff indicated a modified distribution for HG as: heavy-highway at 11.5 percent; utility and municipal at 8.2 percent; residential and commercial at 33.5 percent; and Industrial at 6.8 percent. (Documentation related to the development of this distribution was not available.)

Construction Sector Emission Estimates

The Technical Analysis Division's Area and Mobile Emissions Assessment Section developed the construction portion of the nonroad emission inventory[6]. TNRCC staff stated that construction equipment population numbers contained in the NONROAD defaults are inflated. NONROAD uses number of employees as a surrogate for equipment populations. Because Houston has several large national and international headquarters, the number of office headquarters staff was artificially inflating the true population of equipment present and in use within the Houston area. In fact, TNRCC estimates that defaults may have overestimated the Houston construction equipment population by as much as 2.3 times the locally collected inventory. Because of this concern, TNRCC contracted ERG to develop a local equipment inventory and emission estimate for the HG.

Researchers collected local construction inventories and activity data for eight sectors of the construction industry. These sectors included: heavy-highway, municipalities and counties, municipal/utility, commercial, residential, industrial, cranes, and rental. The heavy-highway sector includes TxDOT-related construction. The ERG documentation provides equipment

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[6] Personal interview with Sam Wells, TNRCC. July 26, 2000.

population estimates by sector in both the text and summary tables, but does not provide a breakdown of emission by construction sector. Correspondence with TNRCC personnel indicated that a breakdown of emissions by sector was not possible due to questions regarding the rental sector (*3, 4*). However, TNRCC staff did indicate relative contributions from several sectors (*3*). Equipment population estimates are the only means for making direct sector comparisons.

TNRCC staff expressed a high degree of confidence in the data taken from the heavy-highway sector in ERG's work. The data from TxDOT were very reliable and cooperation from TxDOT contractors was high. In fact, ERG reports that this sector of the construction group had the highest survey penetration rate during their work for TNRCC.

Equipment activity for heavy-highway construction is allocated based on three different sources in the ERG reports (*11*). Electronic clock hour data served as the basis for activity estimates for two of the respondents. Labor records were the basis for estimating hours of operation for two other respondents, and estimator/field operator estimates were the basis for the remainder of the sources. These are three different sources for a key variable with no explanation given as to how the three measurements were reconciled in the final analysis. Activity data were collected across all sectors for 68.4 percent of the surveyed equipment. When activity estimates were unavailable for a particular equipment category, NONROAD default values were used; thus using a minimum of four different sources. No reconciliation of the differences among data sources, nor the effects, is evident in the ERG reports (*4, 9*).

TNRCC staff also stated that locally developed load factors were used within NONROAD. These load factors represent the average percent use of full throttle on the equipment. Southwest Regional Institute derived data from transient operation research through fuel consumption studies.

The improved TNRCC method for developing construction equipment population and activity data at the local level produces a lower inventory total than the defaults used in the Environmental Protection Agency's NONROAD model. TNRCC staff and the draft ERG documentation (*11*) indicated that the NONROAD model overestimates construction equipment population and activity in the Houston area by more than 50 percent. This overestimation results in an inflated inventory for the construction sector and thus an inflated amount of emissions from the sector. Final ERG documentation reveals default NONROAD NOx emissions stated at over three times that derived from their work, resulting in a significant reduction in that sector's inventory. ERG's results in proving an overestimate of default NONROAD construction equipment emissions are a valuable contribution to the study of state air quality issues.

ERG's work is documented in Appendix V, *Improved Construction Inventory Documentation,* contained in the April 2000 Revision of the *DFW Attainment Demonstration* (*3*). Appendix V documents TNRCC's methods to improve the construction inventory for HG and, by extrapolation, the four-county area of DFW. ERG was contracted by TNRCC to perform a construction equipment population and activity assessment in the HG. Appendix V contains the following three documents:

1. "Documentation for the Dallas Diesel Construction Emissions (DDCE) Project";
2. "Development of a Revised Emission Inventory for Construction Equipment in the Houston-Galveston Ozone Nonattainment Area – Draft Report" by ERG; and
3. "Dallas-Ft. Worth Area Construction Equipment Population Estimates" by ERG. The construction sector emission estimates developed for DFW are based on the draft ERG report (*11*) and do not reflect the lower populations presented in their final report[7].

TNRCC staff recognized that equipment might be used more aggressively once the rule is enforced than under normal operating conditions without the rule. However, there is no quantifiable effect of this response on the emission inventory.

Construction Shift Estimates

Figures 1 and 2 present the calculations estimating the construction shift for both HG and DFW, respectively. In HG, the construction shift rule estimates a 0.8 tons of NOx per day benefit for a total of 171 tons of NOx at a cost of $70 million, or roughly $400,000 per ton of NOx reduced. In DFW, the construction shift rule expects a 0.7 TPD benefit for a total of 107 tons of NOx reduced at a cost of $54 million, or roughly $500,000/ton.

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[7] Trejo, D., and Anderson, S. Cost and Schedule Impact of Texas Natural Resource Conservations Commission Proposed Rule Restricting Construction Equipment. Texas Transportation Institute December 2000. (Unpublished)

Given:

2007 Construction Emissions: 32.1 TPD (*5*)
2007 Area/Nonroad Emission Inventory: 147 TPD (*2*)
2007 NOx Inventory: 1064 TPD (*2*)
Annual duration of proposed rule is 214 days (beginning to end of Daylight Savings Time)
TxDOT-related construction cost is expected to increase 15 to 20 % or $70-93 million annually (*2*)
Heavy-Highway Sector represents 11.5 % of the construction sector (*4*)

Calculations:

Heavy-Highway Sector's Contribution to 2007 Area/Nonroad Inventory
32.1 TPD ÷ 147 TPD × 11.5 % = 2.5 %

Heavy-Highway Sector's Contribution to 2007 NOx Inventory
32.1 TPD ÷ 1064 TPD × 11.5 % = 0.3 %

Heavy-Highway Sector's Contribution to Daily Reduction Benefit from Proposed Rule
6.7 TPD equivalent reduction × 11.5 % = 0.8 TPD

TxDOT's Annual Cost from Proposed Rule

0.8 TPD benefit × 214 day duration of rule each year = 171 tons
$70 million estimated cost ÷ 171 tons = $409,357 / ton

Figure 1. HG Construction Shift Estimate.

Given:

2007 Construction Emissions: 44.98 TPD (3)
2007 Area/Nonroad Emission Inventory: 106.6 TPD (1)
2007 NOx Inventory: 320.5 TPD (1)
Annual duration of proposed rule is 153 days (June 1 to October 31)

TxDOT FY 99 Letting Total for DFW Nonattainment Area = $359 million (6)
TNRCC estimated cost increase to TxDOT-related construction costs = 15-20 % (2)
Heavy-Highway Sector represents 11.5 percent of the construction sector (4)
Ratio of construction shift benefit: combined benefit of construction shift and accelerated purchase of Tier 2/Tier 3 (6.7 TPD / 17.32 TPD) in HG is 39 % (2)

Calculations:

Heavy-Highway Sector's Contribution to 2007 Area/Nonroad Inventory
44.98 TPD ÷ 106.6 TPD × 11.5 % = 4.6 %

Heavy-Highway Sector's Contribution to 2007 NOx Inventory
44.98 TPD ÷ 320.5 TPD × 11.5 % = 1.6 %

Proposed Rule Estimated Daily Benefit
16 TPD × 39 % = 6.24 TPD equivalent reduction

Heavy-Highway Sector's Contribution to Daily Reduction Benefit from Proposed Rule
6.24 TPD equivalent reduction × 11.5 % = 0.7 TPD

TxDOT's Annual Cost from Proposed Rule

$359 million FY 99 Lettings × 15-20 % cost increase = $54-72 million annually
0.7 TPD benefit × 153 day duration of rule each year = 107 tons
$54 million estimated cost ÷ 107 tons = $504,673 / ton

Figure 2. DFW Construction Shift Estimate.

DIESEL ENGINE EMISSION CONTROL ESTIMATE METHODOLOGY

The methodology for estimating cost and emission benefits from using emission control devices was formulated as a sketch-planning tool. Researchers compare the relative cost per ton reduced of various control measures; in particular, the cost per ton of NOx reduced from a construction shift, compared to the cost per ton of using emission control technology. Chapter 2 describes the methodology built upon information from the construction shift estimate and the emission control technology review. The methodology for estimating the emission control cost and benefits involved four steps:

1. selecting viable emission control technologies for the heavy-highway equipment inventories for both HG and DFW,
2. estimating the cost to install the emission controls on the heavy-highway equipment fleet for HG and DFW,
3. estimating the potential NOx reduction from using the emission control equipment installation, and
4. applying the NOx reduction potential of the emission control technology to the heavy-highway sector of the NOx inventory developed from the construction shift estimate.

Emission Control Technologies

The review of emission control technologies in Chapter 2 identified relative costs and emission benefits. Among the control devices reviewed, SCR technologies were chosen as the comparative control measure because of the greater potential for NOx reduction, commercial availability, and a cost representative of other emerging NOx emission control technologies. The selection of SCR for this comparison is not an endorsement of the technology - it is used simply as a representative emission control technology to compare against the construction shift.

The literature suggests that as production of the various emission control devices increases, the cost of those devices should decline. Although PM control devices are generally less expensive to purchase and install, this comparison uses SCR because it offers NOx reduction benefits. SCR was also selected because it can be used with diesel fuel containing 500 ppm sulfur, which will be implemented by 2002 under the Texas LED program. Other NOx reduction emission technologies considered required very low-sulfur diesel fuel (<15 ppm sulfur). Reduction of NOx and PM will be greater as the LED program is fully implemented with the introduction of 15-ppm sulfur by 2006, but immediate reductions are possible beginning in 2002 with the introduction of diesel fuels containing 500 ppm sulfur.

Control Technology Cost (using CARB annualized cost)

Researchers reviewed cost information on SCR systems from the manufacturers and CARB along with the annualized cost estimate from CARB for various control technologies. CARB bases its annualized cost estimates on manufacturer surveys of the current retail price, 500 hours per year operation, a maximum economic life of 10 years, and a 9 percent interest rate. CARB estimates the cost will decline as production volumes increase (*5*). The total cost of installing the NOx reduction control equipment on the heavy-highway nonroad construction equipment inventory for HG and DFW was estimated using the annualized cost for 10 years. Adjusting the annualized cost over a 10-year period, back to the first year NPV, derived the total cost. Although using SCR and placing the entire cost of implementation in the first year may exaggerate actual costs, the estimate is conservative. The actual cost of implementing emission control technologies would likely be less expensive than those represented in this comparison.

Another consideration is the cost per horsepower to implement emission controls. Generally, the cost per horsepower increases for lower horsepower equipment (50-100 hp), and the cost per horsepower decreases for higher horsepower equipment. Most current diesel emission control devices targeting NOx reduction were designed initially for stationary high horsepower diesel equipment (275 hp and greater). As product development improves for mobile equipment and lower horsepower, the cost for emission controls should decline.

Construction Emissions and Equipment Inventories

Attainment Demonstration Documents for the construction shift estimate are the source of NOx emissions inventory data and equipment inventory data used to estimate the cost per ton reduced of implementing emission control technology. According to these sources, the modal horsepower rating for the equipment inventory was 100 hp-175 hp (*3*). Researchers used both maximum value (275 hp) and minimum values (100 hp) in the calculations to provide a conservative range of costs. It assumes that most equipment and most of the NOx emissions from the inventory are below 175 hp. The lower range of NOx emission reduction effectiveness using SCR (65 percent) was calculated to provide a more conservative estimate.

Emission Control Estimate

Researchers estimated the cost of implementing NOx reducing control technology over the entire heavy-highway equipment inventory at $16.9 million to $24.5 million for HG, and $12.2 million to $17.7 million for DFW. The NOx emission reduction was estimated to be 444 tons and 510 tons for HG and DFW, respectively. Therefore, the cost per ton reduction of technology controls for HG is estimated to be $38,000 to $55,000 per ton NOx reduced, and $24,000 to $35,000 per ton NOx reduced in DFW. The emission control estimates for DFW and HG are presented in Figures 3 and 4, respectively.

Control Technology Assumptions
Modal equipment horsepower 100-175 hp (*3*)
HG nonroad diesel construction equipment inventory 845 (*12*)
Minimum estimated NOx reduction from control technology of 65 % (*6*)

Given: CARB estimated annualized cost for 100 hp engine = $3,060 (*5*)
Rounded NPV (P/A) annualized cost for 10 years on 100 hp engine: $3,060 × (6.418) = $19,640 ea = $20,000
CARB estimated annualized cost for 275 hp engine = $4,460 (*5*)
Rounded NPV (P/A) annualized cost for 10 years on 275 hp engine: $4,460 × (6.418) = $28,624 ea = $29,000

Calculations for Cost of NOx Control Technology for Construction Equipment Inventory
845 pieces × $20K ea. per 100 hp = $16,900,000 for 10 year cost of technology control
845 pieces × $29K ea. per 275 hp = $24,505,000 for 10 year cost of technology control

NOx Inventory Assumptions
2007 HG Construction NOx Emissions: 32.1 TPD (*12*)
2007 Area/Nonroad Emission Inventory: 147 TPD (*2*)
2007 NOx Inventory: 1064 TPD (*2*)
Annual duration of proposed rule is 214 days (beginning to end of Daylight Savings Time)
Heavy-Highway Sector represents 11.5 percent of the construction sector (*4*)

NOx Inventory Calculations
Heavy-Highway Sector Contribution to 2007 Area/Nonroad Inventory: 32.1 TPD ÷ 147 TPD × 11.5 % = 2.5 %
Heavy-Highway Sector Contribution to 2007 NOx Inventory: 32.1 TPD ÷ 1064 TPD × 11.5% = 0.3 %
Heavy-highway Sector NOx Contribution TPD: 0.3 % × 1064 TPD = 3.19 TPD
Heavy-highway Sector NOx Contribution: tons 3.19 TPD × 214 Days = 683 Tons

65 % Reduction from NOx Control Equipment: 683 tons × 65 % = 444 tons reduced

Cost per ton Range
Cost of Control Technology per ton reduced: $16,900,000 ÷ 444 tons = $38,063 per ton
Cost of Control Technology per ton reduced: $24,505,000 ÷ 444 tons = $55,191 per ton

$38,000 to $55,000 per ton NOx reduced

30 % Reduced Implementation and 30 % Reduced Efficiency Alternative
254 pieces × $20K ea. per 100 hp = $5,080,000 for 10-year cost of technology control
254 pieces × $29K ea. per 275 hp = $7,366,000 for 10-year cost of technology control

w/ 30 % reduction efficiency on 30 % of equipment = 9 % reduction × 683 tons = 61 tons
$5,080,000 ÷ 61 tons = $83,278 per ton
$7,366,000 ÷ 61 tons = $120,754 per ton

$83,000 to $121,000 per ton reduced

Figure 3. HG Emission Control Technology Cost Estimate.

Control Technology Assumptions
Modal equipment horsepower 100-175 hp (*3*)
DFW nonroad diesel construction equipment inventory 610 (*12*)
Minimum estimated NOx reduction from control technology of 65 % (*6*)

Given: CARB estimated annualized cost for 100 hp engine = $3,060 (*5*)
Rounded NPV (P/A) annualized cost for 10 years on 100 hp engine: $3,060 × (6.418) = $19,640 ea = $20,000
CARB estimated annualized cost for 275 hp engine = $4,460 (*5*)
Rounded NPV (P/A) annualized cost for 10 years on 275 hp engine: $4,460 × (6.418) = $28,624 ea = $29,000

Calculations for Cost of NOx Control Technology for Construction Equipment Inventory
610 pieces × $20K ea. per 100 hp = $12,200,000 for 10-year cost of technology control
610 pieces × $29K ea. per 275 hp = $17,690,000 for 10-year cost of technology control

NOx Inventory Assumptions
2007 DFW Construction NOx Emissions: 44.98 TPD (*3*)
2007 Area/Nonroad Emission Inventory: 106 TPD (*1*)
2007 NOx Inventory: 320.5 TPD (*1*)
Annual duration of proposed rule is 153 days (June 1 – October 31)
Heavy-Highway Sector represents 11.5 % of the construction sector (*11*)

NOx Inventory Calculations
Heavy-Highway Sector's Contribution to 2007 Area/Nonroad Inventory: 44.98 TPD ÷ 106 TPD × 11.5 % = 4.65 %
Heavy-Highway Sector's Contribution to 2007 NOx Inventory: 44.98 TPD ÷ 320.5 TPD × 11.5 % = 1.6 %
Heavy-highway Sector NOx Contribution TPD: 1.6 % × 320.5 TPD = 5.13 TPD
Heavy-highway Sector NOx Contribution Tons: 5.13 TPD × 153 Days = 784.6 tons

65 % Reduction from NOx Control Equipment: 784.6 tons × 65 % = 510 tons

Cost per ton Range
Cost of Control Technology per ton reduced: $12,200,000 ÷ 510 tons = $23,921 per ton
Cost of Control Technology per ton reduced: $17,690,000 ÷ 510 tons = $34,682 per ton

$24,000 to $35,000 per ton NOx reduced

30% Reduced Implementation and 30% Reduced Efficiency Alternative
183 pieces × $20K ea. per 100 hp = $3,660,000 for 10-year cost of technology control
183 pieces × $29K ea. per 275 hp = $5,307,000 for 10-year cost of technology control

30% reduction efficiency on 30% of equipment = 9% reduction × 510 tons = 46 tons
$3,660,000 ÷ 46 tons = $79,565 per ton
$5,307,000 ÷ 46 tons = $115,3691 per ton

$80,000 – $115,000 per ton NOx reduced

Figure 4. DFW Emission Control Technology Cost Estimate.

CONTROL MEASURE COMPARISON

Tables 7 through 11 compare the following control measures:

- construction shift based on TNRCC estimated emission and cost,
- construction shift based on TNRCC emissions estimate and TTI estimated cost impact, (7)
- use of SCR as emission control technology on the heavy-highway fleet,
- limited use (30 percent) and limited NOx reduction (30 percent) of SCR,
- LED fuel program, and
- accelerated purchase program.

Construction Shift Comparison

The construction shift in HG is estimated to produce a NOx reduction benefit of 0.8 TPD, or a total of 171 tons during the 214 days of Daylight Savings Time, from the heavy-highway sector. The cost of the shift to TxDOT, based on TNRCC estimates, would be $70 million annually, resulting in a cost of roughly $400,000 per ton of NOx reduced. (See Table 7).

TTI adjusted the cost impact of the construction shift for HG and DFW based on a survey of contractors and TxDOT personnel from each nonattainment area. Cost and duration impacts for various types of construction projects and alternative work schedules were developed from the survey information. Researchers found the total cost impact was 12 percent for HG, and 16 percent for DFW area (7).

Assuming $490 million in annual lettings for fiscal year 1999 in HG, TTI estimated the total cost impact of the construction shift to be approximately $59 million, or $344,000 per ton of NOx reduced. Table 7 also presents this information.

Table 7. Construction Shift for HG.

Control Measure	Description	Heavy-highway NOx Benefit	Estimated Cost	Effectiveness
Construction shift based on SIP and attainment demonstration	Approved by TNRCC. 214-day duration (during Daylight Savings Time).	0.8 TPD (or 171 tons annually)	$70 million (annually)	$409,000 per ton
Construction shift based on TTI total cost impact	TTI comparison 214-day duration (during Daylight Savings Time)	0.8 TPD (or 171 tons annually)	$59 million (annually)	$344,000 per ton

Using TNRCC cost estimates, the construction shift in DFW is expected to cost $54 million annually and yield 107 tons of NOx reduced for approximately $505,000 per ton of NOx reduced. In DFW, TTI estimated the total cost impact of the construction shift to be approximately $57 million annually, or $537,000 per ton of NOx reduced based on $359 million in annual lettings. See Table 8.

Table 8. Construction Shift for DFW.

Control Measure	Description	Heavy-highway NOx Benefit	Estimated Cost	Effectiveness
Construction shift based on SIP and attainment demonstration	Approved by TNRCC. 153-day duration (June 1–October 31)	0.7 TPD (107 tons annually)	$54 million (annually)	$505,000 per ton
Construction shift based on TTI totals cost impact	TTI comparison. 153-day duration (June 1–October 31)	0.7 TPD (107 tons annually)	$57 million (annually)	$537,000 per ton

Emission Control Comparison

As presented in Table 9, the estimated cost for installing SCR on the entire heavy-highway fleet in HG is between $17 million and $24 million and will yield an estimated NOx reduction of 2.1 TPD, or approximately 444 tons annually. In Table 10, DFW's cost of implementing emission controls is estimated at $12.2 to $17 million.

Since full implementation is unlikely to occur, an alternative scenario was estimated for both the HG and DFW area. This partial implementation scenario uses the same basic assumption except that it implements the SCR emission controls on 30 percent of the fleet, and assumes that the emission control is only 30 percent effective.

The DFW full implementation should achieve 0.3 TPD NOx reductions for a total of 510 tons. The partial implementation scenario results in NOx reduction cost of approximately $80,000 to $120,000 per ton of NOx reduced for HG and DFW.

Table 9. HG Emission Control Cost.

Control Measure	Description	Heavy-highway NOx Benefit	Estimated Cost	Effectiveness
Emission control technology using SCR on entire heavy-highway fleet	Comparison using SCR NOx emission reduction equipment on heavy-highway sector assuming modal hp 100-175 hp and 845 pieces	2.1 TPD (444 tons annually)	$17 million to $24 million	$38,000 per ton to $55,000 per ton
Partial implementation of control technology 30 percent of fleet and 30 percent NOx reduction efficiency	Comparison using SCR NOx emission reduction equipment on heavy-highway sector assuming modal hp 100-175 hp and 254 pieces	0.28 TPD (61 tons annually)	$5.1 million to $7.4 million	$83,000 per ton to $121,000 per ton

Table 10. DFW Emission Control Cost.

Control Measure	Description	Heavy-highway NOx Benefit	Estimated Cost	Effectiveness
Emission control technology using SCR	TTI Comparison for DFW Using SCR NOx emission control on heavy-highway sector assuming modal HP 100-175 hp and 610 pieces	3.3 TPD (510 tons annually)	$12.2 million to $17.7 million	$24,000 per ton to $35,000 per ton
Partial implementation of control technology 30 percent of fleet and 30 percent NOx reduction efficiency	Comparison using SCR NOx emission reduction equipment on heavy-highway sector assuming modal hp 100-175 hp and 183 pieces	0.3 TPD (46 tons annually)	$3.7 million to $5.3 million	$80,000 per ton to $115,000 per ton

LED and Accelerated Purchase

Tables 11 and 12 present the estimates for both costs and emissions benefits from both the LED and accelerated purchase control measures. Unlike the previous comparisons, the cost and emission benefit information in Tables 11 and 12 rely heavily on information from regulatory impact analyses from TNRCC and EPA sources.

The rule's regulatory impact analysis assumes the NOx reduction benefit of the LED program is 7 percent. This rule was applied to the heavy-highway NOx inventory for both HG and DFW. Defining the cost for the program per piece of equipment was difficult because various estimates from industry and regulatory agencies usually gave only fuel cost increases, or costs for the entire program. Therefore, researchers found it difficult to separate out the cost for the heavy-highway equipment sector. The equipment cost estimate is based on EPA's *Draft Regulatory Impact Analysis for the Proposed Heavy-Duty Engine and Vehicle Standards and Highway Diesel Sulfur Requirements Rule* (*4*). In this report, EPA calculated the long-term incremental cost of $0.044 per gallon for low-sulfur diesel fuel and calculated the cost per vehicle by class and average fuel economy. Researchers then brought back total fuel cost to a total net present value in the year of sale per vehicle and yielded the following costs: $536 for light heavy-duty vehicle; $1,004 for a medium heavy-duty vehicle; $3,704 for a heavy heavy-duty vehicle; and $4,364 for an urban bus.

Researchers also took emission benefits from the accelerated purchase program from the regulatory impact analyses reported by TNRCC where available. The NOx benefit for the accelerated purchase program is taken from EPA estimates of 40 percent PM reductions and 60 percent NOx reduction over the entire length of the program. Researchers could not locate and identify the cost information for the HG accelerated purchase program contained in an appendix to the SIP and attainment demonstration documents.

Comparison Summary

The combined comparison for HG and DFW are presented in Tables 13 and 14, respectively.

Table 11. HG LED and Accelerated Purchase Comparison.

Control Measure	Description	Heavy-Highway NOx Benefit	Estimated Cost	Effectiveness
LED Program: < 500 ppm < 10 percent aromatic HC > 48 cetane	Approved by TNRCC LED Program begins April 1, 2005, requires diesel fuel produced for delivery and sale shall not exceed 500 ppm sulfur, less than 10 percent by vol. aromatic HC, and cetane number of 48 or greater	0.22 TPD 48 tons (7 percent by TNRCC)	*$2.6 million Cost range: $0.04 per gal - $0.14 per gal	*$54,000/ton based on $0.044 per gal.
Accelerated Purchase Tier 2 equipment fleet 50-100 hp: 25 percent Tier 2 by end 2004 50 percent Tier 2 by end 2005 75 percent Tier 2 by end 2006 100 percent Tier 2 by end 2007	Approved by TNRCC Tier 2 equipment fleet 100-175 hp: 10 percent Tier 2 by end 2004 20 percent Tier 2 by end 2005 30 percent Tier 2 by end 2006 50 percent Tier 2 by end 2007	**60 percent NOx **40 percent PM NA	NA	NA

*Net present value cost based on EPA 15 ppm LED lifetime cost per piece in first year, modal HP 100-175, equip, 845 pieces @ $3,704 ea. = $2,597,530, 7 percent reduction for 48 tons reduced = $54,000/ton.

**Based on EPA estimates for entire span of program.

NA – not available

Table 12. DFW LED and Accelerated Purchase Comparison.

Control Measure	Description	Heavy-highway NOx Benefit	Estimated Cost	Effectiveness
LED Program < 500 ppm < 10 percent aromatic HC > 48 cetane	Approved by TNRCC. LED Program begins April 1, 2005, requires diesel fuel produced for delivery and sale shall not exceed 500 ppm sulfur, less than 10 percent by vol. aromatic HC, and cetane number of 48 or greater	0.31 TPD 47 tons (7 percent by TNRCC)	*$2,259,440 Cost range: $0.04 per gal. - $0.14 per gal.	*$48,000 per ton* (based on $0.044 per gal)
Accelerated Purchase Tier 2 equipment 50-100 hp 25 percent Tier 2 by end of 2004 50 percent Tier 2 by end of 2005 75 percent Tier 2 by end of 2006 100 percent Tier 2 by end of 2007	Approved by TNRCC. 100-175 hp 10 percent Tier 2 by end of 2004 20 percent Tier 2 by end of 2005 30 percent Tier 2 by end of 2006 50 percent Tier 2 by end of 2007	**60 percent NOx **40 percent PM	NA	$8,700 per ton- $11,700 per ton (based on TNRCC Ch 114 p. 10 preamble

*Net present value cost based on EPA 15 ppm LED lifetime cost per piece in first year, modal HP 100-175, equip, 610 pieces @ $3,704 ea. = $2,597,530, 7 percent reduction for 48 tons reduced = $48,000/ton.

**Based on EPA estimates for entire span of program.

NA – not available

Table 13. HG Control Measure Comparison Summary.

Control Measure	Description	Heavy-highway NOx Benefit	Estimated Cost	Effectiveness
Construction shift based on SIP and attainment demonstration	Approved by TNRCC. 214-day duration (during Daylight Savings Time).	0.8 TPD for 171 tons annually	$70 million (annually)	$409,000 per ton
Construction shift based on TTI total cost impact	TTI comparison 214-day duration (during Daylight Savings Time)	0.8 TPD (or 171 tons annually)	$59 million (annually)	$344,000 per ton
Emission control technology using SCR on entire heavy-highway fleet	Comparison using SCR NOx emission reduction equipment on heavy-highway sector assuming modal hp 100-175 hp and 845 pieces	2.1 TPD (444 tons annually)	$17 million to $24 million	$38,000 per ton to $55,000 per ton
Partial implementation of control technology 30 percent of fleet and 30 percent NOx reduction efficiency	Comparison using SCR NOx emission reduction equipment on heavy-highway sector assuming modal hp 100-175 hp and 254 pieces	0.28 TPD (61 tons annually)	$5.1 million to $7.4 million	$83,000 per ton to $121,000 per ton
LED Program: < 500 ppm < 10 percent aromatic HC > 48 cetane	Approved by TNRCC. LED Program begins April 1, 2005, requires diesel fuel produced for delivery and sale shall not exceed 500 ppm sulfur, less than 10 percent by vol. aromatic HC, and cetane number of 48 or greater	0.22 TPD 48 tons (7 percent by TNRCC)	*$2.6 million Cost range: $0.04 per gal - $0.14 per gal	*$54,000/ton based on $0.044 per gal.
Accelerated Purchase Tier 2 equipment fleet 50-100 hp: 25 percent Tier 2 by end of 2004 50 percent Tier 2 by end of 2005 75 percent Tier 2 by end of 2006 100 percent Tier 2 by end of 2007	Approved by TNRCC Tier 2 equipment fleet 100-175 hp: 10 percent Tier 2 by end of 2004 20 percent Tier 2 by end of 2005 30 percent Tier 2 by end of 2006 50 percent Tier 2 by end of 2007	**60 percent NOx **40 percent PM NA	NA	NA

*Net present value cost based on EPA 15 ppm LED lifetime cost per piece in first year, modal HP 100-175, equipment, 845 pieces @ $3,704 ea. = $2,597,530, 7 percent reduction for 48 tons reduced = $54,000/ton.

**Based on EPA estimates for entire span of program.

NA – not avaialble

Table 14. DFW Control Measure Comparison Summary

Control Measure	Description	Heavy-highway NOx Benefit	Estimated Cost	Effectiveness
Construction shift based on SIP and attainment demonstration	Approved by TNRCC. 153-day duration (June 1-October 31)	0.7 TPD (107 tons annually)	$54 million (annually)	$505,000 per ton
Construction shift based on TTI totals cost impact	TTI comparison. 153-day duration (June 1-October 31)	0.7 TPD (107 tons annually)	$57 million (annually)	$537,000 per ton
Emission control technology using SCR	TTI Comparison for DFW Using SCR NOx emission control on heavy-highway sector assuming modal HP 100-175 hp and 610 pieces	3.3 TPD (510 tons annually)	$12.2 million to $17.7 million	$24,000 per ton to $35,000 per ton
Partial implementation of control technology 30 percent of fleet and 30 percent NOx reduction efficiency	Comparison using SCR NOx emission reduction equipment on heavy-highway sector assuming modal hp 100-175 hp and 183 pieces	0.3 TPD (46 tons annually)	$3.7 million to $5.3 million	$80,000 per ton to $115,000 per ton
LED Program < 500 ppm < 10 percent aromatic HC > 48 cetane	Approved by TNRCC. LED Program begins April 1, 2005, requires diesel fuel produced for delivery and sale shall not exceed 500 ppm sulfur, less than 10 percent by vol. aromatic HC, and cetane number of 48 or greater	0.31 TPD 47 tons (7 percent by TNRCC)	*$2,259,440 Cost range: $0.04 per gal. - $0.14 per gal.	*$48,000 per ton* based on $0.044 per gal
Accelerated Purchase Tier 2 equipment 50-100 hp 25 percent Tier 2 by end of 2004 50 percent Tier 2 by end of 2005 75 percent Tier 2 by end of 2006 100 percent Tier 2 by end of 2007	Approved by TNRCC. 100-175 hp 10 percent Tier 2 by end of 2004 20 percent Tier 2 by end of 2005 30 percent Tier 2 by end of 2006 50 percent Tier 2 by end of 2007	**60 percent NOx **40 percent PM	NA	$8,700 per ton-$11,700 per ton (based on TNRCC Ch 114 p. 10 preamble)

*Net present value cost based on EPA 15 ppm LED lifetime cost per piece in first year, modal HP 100-175, equipment, 610 pieces @ $3,704 ea. = $2,597,530, 7 percent reduction for 48 tons reduced = $48,000/ton.
**Based on EPA estimates for entire span of program.
NA – not available

CHAPTER FOUR – CONCLUSIONS

TNRCC expects an estimated 21 and 13 percent emission reduction from the construction industry through the proposed equipment ban in the HG and DFW areas, respectively. This reduction will come at a cost to TxDOT and other government agencies as well as to private business. TxDOT may pay $400,000 to $500,000 per ton of NOx reduction as a result of this rule. In comparison, emission control devices cost four to ten times less. The review and assessment of diesel engine emissions presented herein indicate that implementing after-treatment emission controls would range from $24,000 to $55,000 per ton of NOx reduction across the entire fleet, and $80,000 to $120,000 per ton of NOx reduction if controls are partially implemented.

Alternative control measures for construction projects, such as diesel engine emission controls, have the potential to allow equipment to operate during normal working hours and still provide NOx emission reductions. The costs of these controls should be carefully evaluated against anticipated cost increases to TxDOT, letting costs in response to the construction shift rule. If using after-treatment emission controls shows a cost savings, perhaps incentives encouraging or accelerating their adoption into the heavy-highway fleet should be developed and assessed. For example, NOx reduction credits could be used as a contracting performance measure in the same way that time and duration contract performance measures are used in construction contracts. Or, funding assistance could provide construction equipment owners and contractors encouragement to retrofit equipment with NOx emission controls sooner than those scheduled in the accelerated purchase rules. In any case, a host of control measure options should be explored and assessed as alternatives to a construction shift.

The California legislature created the Carl Moyer Memorial Air Quality Standards Attainment Program in 1999 to pay for the incremental cost of repower, retrofit, and purchase of cleaner engines that meet a specified cost-effectiveness level for NOx reduction. The $50 million fund has significantly reduced NOx and PM emissions from heavy-duty vehicles and equipment traditionally powered by diesel engines. With the first year's funding, the Carl Moyer Program reduced NOx emissions by approximately four TPD and reduced particulate matter emissions statewide by approximately 100 pounds per day. The types of projects being funded include: purchase of new natural gas transit and school buses; purchase of new natural gas and dual-fuel trucks; purchase of electric forklifts instead of internal combustion forklifts; and replacement of old diesel engines with newer diesel engines in marine vessels, agricultural pumps, and other off-road equipment. This type of program has the potential to offset the relatively high cost NOx reduction control measures in nonattainment areas in Texas. (For more information see http://arbis.arb.ca.gov/msprog/moyer/moyer.htm.)

Alternative control measures have the potential to offer similar or greater NOx reduction benefits for less money. However, the after-treatment approach to emission control presents challenges of its own such as: the limited commercial availability of NOx after-treatment devices over a broad range of engine horsepower; long-term reliability and maintenance; reduced fuel efficiency; and the evolving nature of emission control technology. The primary benefit of using after-treatment will be the potential to achieve greater NOx reductions sooner. It is also important to note the emission benefits estimated within this report are calculated only during the construction shift period. Emission benefits from emission control devices on heavy-highway equipment would actually occur year round, producing even greater reductions. Over the next five to ten years, the implementation of cleaner diesel fuel and accelerated purchase should achieve significant NOx benefits. In the interim, a variety of control measures should be assessed for effectiveness.

In general, the results of this assessment indicate:

- The use of diesel engine emission control devices targeted to reduce NOx emissions are more cost effective than the construction shift when measured in dollars per ton of NOx reduced.
- The cost of using diesel engine emission control technology (after-treatments and retrofits) is generally less than the cost of the construction shift, and provides greater NOx emission reductions.
- The NOx reduction potential is greatest when diesel engine emission control devices are combined with the use of low-sulfur diesel fuel.
- Engine emission control and accelerated purchase are more cost effective than construction shifts. Even using conservative assumptions, NOx reductions using emission control after-treatment devices range from $25,000 to $55,000 per ton.

- The cost estimate for TxDOT by TNRCC on the impact of a construction shift is of the same order of magnitude as that developed by TTI. Both estimates indicate the cost per ton of NOx reduction to be more than $400,000 per ton.
- The cost effectiveness of the LED program appears to be greater than that of the construction shift strategies.

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(*1*) Texas Natural Resource Conservation Commission. *DFW Attainment Demonstration,* April 2000.

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(*3*) Texas Natural Resource Conservation Commission. *Improved Construction Inventory Documentation.* Appendix V contained in *DFW Attainment Demonstration.* April 2000.

(*4*) Environmental Protection Agency, Assessment and Standards Division, Office of Transportation and Air Quality. Draft Regulatory Impact Analysis for the Proposed Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements Rule. Report EPA420-D-00-001, May 2000.

(*5*) California Air Resources Board, Stationary Source Division, Mobile Source Control Division. *Risk Reduction Plan to Reduce PM Emission from Diesel-Fueled Engines and Vehicles*, October 2000.

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(*9*) Texas Natural Resource Conservation Commission. *Texas Natural Resource Conservation Commission Regulatory Impact Analysis.* Chapter 114 - Control of Air Pollution from Motor Vehicles, Rule Log Number 2000-011D-114-AI for Low Emission Diesel (LED) Fuel, December 2000.

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(*12*) Eastern Research Group, Inc., and Starcrest Consulting Group, LLC. "Development of a Revised Emissions Inventory for Construction Equipment in the Houston-Galveston Ozone Nonattainment Area – Final Report," April 20, 2000.

APPENDIX – DIESEL GLOSSARY[8]

Aftercooling / Intercooling - Cooling the engine intake air after the turbocharger and prior to introduction into the cylinder. Aftercooling increases engine power and lowers NOx emissions.

After-Treatment Devices - Devices that remove pollutants from exhaust gases after the gas leaves combustion chamber (e.g., catalytic converters or diesel particulate filters). The term "exhaust gas after-treatment" is considered derogatory by the emission control industry, but there is no consensus on the use of such alternatives as "post-combustion treatment" or "exhaust emission control."

Alternative Fuel - Fuel other than petroleum diesel or gasoline.

Bi-Fueled Vehicle - A vehicle with two separated fuel systems designed to run on either conventional fuel or an alternative fuel using only one fuel at a time.

Biodiesel - The mono alkyl esters of long chain fatty acids derived from renewable lipid feedstocks, such as vegetable oils and animal fats, for use in compression ignition (diesel) engines. Manufactured by transestrification of the organic feedstock by methanol.

Brake Mean Effective Pressure (BMEP) - The work accomplished during one engine cycle divided by the engine swept volume. It is essentially the engine torque normalized by the engine displacement. The word "brake" denotes the actual torque/power available at the engine flywheel as measured on a dynamometer. Thus, BMEP is a measure of the useful power output of the engine.

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[8] Glossary taken from: Reduction Plan to Reduce PM Emission from Diesel-Fueled Engines and Vehicles. California Air Resources Board, Stationary Source Division, Mobile Source Control Division. October 2000.

California Air Resources Board (CARB) - A state regulatory agency charged with regulating the air quality in California.

Carbon Dioxide (CO_2) - A colorless, odorless, non-toxic gas. It is one of main products of fossil-fuel combustion. Carbon dioxide is a greenhouse gas that contributes to the potential for global warming.

Carbon Monoxide (CO) - A colorless, odorless, and toxic gas. It blocks the lungs' ability to obtain oxygen. CO is produced by incomplete combustion of fossil fuels and is a major part of air pollution. Compression ignition (diesel) engines generate significantly lower CO emissions than spark ignited engines.

Catalyst - A substance which influences the rate of a chemical reaction but is not one of the original reactants or final products, i.e., it is not consumed or altered in the reaction. Catalysts are used in many processes in the chemical and petroleum industries. Emission control catalysts are used to promote reactions that change exhaust pollutants from internal combustion engines into harmless substances.

Cetane Index - A calculated value, derived from fuel density and volatility, giving a reasonably close approximation to cetane number.

Cetane Number - A measure of ignition quality of diesel fuel. The higher the cetane number the easier the fuel ignites when injected into an engine. Cetane number is determined by an engine test using two reference fuel blends of known cetane numbers. The reference fuels are prepared by blending normal cetane (n-hexadecane), having a value of 100, with heptamethyl nonane, having a value of 15.

Clean Air Act (CAA) - In the U.S., the fundamental legislation to control air pollution. The original Clean Air Act was signed in 1963. The law set emissions standards for stationary sources, such as factories and power plants. Criteria pollutants included lead, ozone, CO, SO_2, NOx, and PM, as well as air toxics. The CAA was amended several times, most recently in 1990. The Amendments of 1970 introduced motor vehicle emission standards for automobiles and trucks.

Clean-Fuel Vehicle (CFV) - A vehicle that has been certified to meet clean-fuel standards of the Clean Air Act Amendments of 1990.

Cloud Point (CP) - A measure of the ability of a diesel fuel to operate under cold weather conditions. Defined as the temperature at which wax first becomes visible when diesel fuel is cooled under standardized test conditions (ASTM D2500).

Common Rail Injection - A diesel fuel injection system employing a common pressure accumulator, called the rail, which is mounted along the engine block. A high-pressure fuel pump feeds the rail. Solenoid valves activate the injectors, which are fed from the common rail. The solenoid valves and the fuel pump are electronically controlled. In the common rail injection system the injection pressure is independent from engine speed and load. Therefore, the injection parameters can be freely controlled. Usually a pilot injection is introduced, which allows for reductions in engine noise and NOx emissions.

Compressed Natural Gas (CNG) - Natural gas compressed to a volume and density that is practical as a portable fuel supply.

Compression Ignition (CI) - The form of ignition that initiates combustion in a diesel engine. The rapid compression of air within the cylinders generates the heat required to ignite the fuel as it is injected.

Cordierite - A ceramic material of the formula $2MgO\text{-}2Al_2O_3\text{-}5SiO_2$ which is used for automotive flow-through catalyst substrates and ceramic wall-flow diesel filters.

Diesel Oxidation Catalyst (DOC) - Catalyst promoting oxidation processes in diesel exhaust. Usually designed to reduce emissions of the organic fraction of diesel particulates, gas-phase hydrocarbons, and carbon monoxide.

Diesel Particulate Filter (DPF) - A device that physically captures diesel particulates preventing their discharge from the tailpipe. Collected particulates need to be removed from the filter, usually by continuous or periodic oxidation in a process called "regeneration."

Diesel Particulate Matter (DPM) - Sub-micron size particles found in diesel exhaust. Most emission regulations specify DPM measurement methods in which particulates are sampled on filters from cooled exhaust gas. The cooling causes condensation of vapors in the gas sampling train. Thus, the DPM is composed of both solid and liquid particles and is generally classified into three fractions: (1) inorganic carbon (soot), (2) organic fraction (often referred to as SOF or VOF), and (3) sulfate fraction (hydrated sulfuric acid).

Direct Injection (DI) - In diesel engines with direct injection the combustion chamber is not divided and fuel is injected directly to the cylinder.

Dual-Fuel Vehicle - A vehicle designed to operate on a combination of alternative fuel, such as compressed natural gas (CNG) or liquefied petroleum gas (LPG), and conventional fuel, such as diesel or gasoline. These vehicles have two separate fuel systems, which inject both fuels simultaneously into the engine combustion chamber.

Electronic Control Module (ECM) - A microprocessor that determines the beginning and end of each injection cycle on every cylinder. The ECM determines both fuel metering and injection timing in response to such parameters as engine crankshaft position and rpm, engine coolant and intake air temperature, and absolute intake air boost pressure.

Elemental Carbon (EC) - Inorganic carbon, as opposed to carbon in organic compounds, sometimes used as a surrogate measure for diesel particulate matter, especially in occupational health environments. Elemental carbon usually accounts for 40-60 percent of the total DPM mass.

Emission Credit Trading - A program administered by the Environmental Protection Agency under which low polluters are awarded credits which may be traded on a regulated market and purchased by polluters who are in noncompliance for emissions until compliance can be achieved.

Evaporative Emissions - Hydrocarbon vapors that escape from a fuel storage tank or a vehicle fuel tank or vehicle fuel system.

Flash Point - The temperature at which a combustible liquid gives off just enough vapor to produce a vapor/air mixture that will ignite when a flame is applied. The flash point is measured in a standardized apparatus using standard test methods, such as ASTM D93 or ISO 2719.

Flexible-Fueled Vehicle - A vehicle with the ability to operate on alternative fuels, 100 percent petroleum-based fuels, or a mixture of alternative fuel and petroleum-based fuels.

Fuel Cycle - The processes involved in extracting a fuel in its native form, converting it to a useful product, transporting it to market, and consuming it at its final destination.

Geometric Surface Area (GSA) - In monolith catalyst substrates, the total channel surface area per unit of substrate volume.

Hybrid Electric Vehicle (HEV) –Various types of electric vehicles that use another power source to propel the vehicle or generate power for an electric drive train, or a combination of the two types.

Hydraulic/Electronic Unit Injector (HEUI) - A type of unit injector actuated by engine oil pressure rather than the camshaft. A separate oil pump creates very high oil pressure (up to 3,000 psi). This high pressure is routed to every injector through a gallery. The engine's Electronic Control Module varies the pressure in response to engine speed and other parameters.

Ignition Delay - The length of time or number of degrees of crankshaft rotation between the beginning of injection and ignition of the fuel.

In-Direct Injection (IDI)- In diesel engines with in-direct injection the fuel is injected to an auxiliary pre-chamber. Combustion starts in the prechamber and propagates to the cylinder.

Injection Period - The time, measured in degrees of crankshaft rotation, between the beginning and end of injection. On engines with hydromechanical injection systems, it is controlled by the opening and closing of ports in the injector body or by the action of a plunger forcing fuel out of a cup. On electronic injection systems, it is determined directly or indirectly by the action of a solenoid valve.

In-Line Injection Pump - An injection pump with a separate cylinder and plunger for each engine cylinder. Each plunger is rotated by a rack to determine metering via ports in the body of the pump and helical cuts on the pump plungers. The plungers are driven off a camshaft, which usually incorporates a centrifugal or electronically controlled timing advance mechanism.

Lean NOx Catalyst (LNC) - Catalyst designed to reduce nitrogen oxides from diesel or spark ignited engine exhaust gases under net oxidizing conditions, i.e., in the presence of excessive amounts of oxygen.

Liquefied Natural Gas (LNG) - Natural gas that has been refrigerated to cryonic temperatures where the gas condenses into a liquid.

Liquefied Petroleum Gas (LPG) - Liquefied Petroleum Gas (LPG) is a mixture of low-boiling hydrocarbons that exists in a liquid state at ambient temperatures when under moderate pressures (less than 1.5 MPa or 200 psi). LPG is a byproduct from the processing of natural gas and from petroleum refining. Major components of LPG are propane (min. 85 percent content in the U.S.), butane, and propylene.

Low Emission Vehicle (LEV) - A vehicle that is certified to meet the LEV emission standards set by the California Air Resources Board (CARB).

National Ambient Air Quality Standards (NAAQS) - Ambient standards for six pollutants including ozone, carbon monoxide, nitrogen dioxide, lead, particulate matter, and oxides of sulfur specifically regulated under the U.S. Clean Air Act of 1990. Urban areas are required to achieve attainment in regards to ambient concentrations of these criteria pollutants.

Natural Gas (NG) - Mixture of hydrocarbon compounds and small quantities of various non-hydrocarbon components existing in the gas phase or in solution with crude oil in natural underground reservoirs. The main component of natural gas is methane.

Nitrogen Oxides (NOx) - Several air-polluting gases composed of nitrogen and oxygen that play an important role in the formation of photochemical smog. Nitrogen oxides are collectively referred to as "NOx," where "x" represents a changing proportion of oxygen to nitrogen. Internal combustion engines are significant contributors to the worldwide nitrogen oxide emissions. For the purpose of emission regulations, NOx is composed of colorless nitric oxide (NO) and the reddish-brown, very toxic and reactive nitrogen dioxide (NO_2). Other nitrogen oxides, such as nitrous oxide N_2O (the anesthetic "laughing gas"), are not regulated emissions.

NMHC - Non-Methane Hydrocarbons.

Nonattainment Area - A region that exceeds the U.S. National Ambient Air Quality Standards (NAAQS) for one or more criteria pollutants. Such regions, or areas, are required to seek modifications to their State Implementation Plans (SIPs), setting forth a reasonable timetable using means that are approved by the Environmental Protection Agency (EPA) to achieve attainment of NAAQS by a certain date. Under the Clean Air Act, if a nonattainment area fails to attain NAAQS, the EPA may superimpose a Federal Implementation Plan (FIP) with stricter requirements. Also, the EPA may impose fines, construction bans, or cutoffs in Federal grant revenues until the area achieves applicable NAAQS.

Original Equipment Manufacturer (OEM) - Manufacturers of equipment (such as engines, vehicles, etc.) that provide the original product design and materials for its assembly and manufacture. OEMs are directly responsible for manufacturing and modifying the products, making them commercially available, and providing the warranty.

Overhead Cam - A camshaft used for operating both valves and unit injectors, located on top of or within the cylinder head. Such camshafts are driven by a multi-gear gear train off the crankshaft. They simplify the design of the cylinder head and eliminate pushrods, allowing for much larger, open intake and exhaust ports and better breathing.

Oxygenated Fuel - Any fuel substance containing oxygen, such as ethanol, methanol, or biodiesel. Oxygenated fuel tends to give a more complete combustion of its carbon into carbon dioxide (CO_2), thereby reducing emissions of hydrocarbons and carbon monoxide. Oxygenated fuels may result in increased nitrogen oxides emissions.

Ozone (O_3) - An oxygen molecule with three oxygen atoms. The stratosphere ozone layer, which is a concentration of ozone molecules located at 10 to 50 kilometers above sea level, is in a state of dynamic equilibrium. Oxygen molecules absorb ultraviolet (UV) light to form ozone that, in turn, decomposes back to oxygen. These processes absorb most of the ultraviolet light from the sun, shielding life from the harmful effects of UV radiation. Ozone is normally present at ground level in low concentrations. In cities where high levels of air pollutants are present, the action of the sun's ultraviolet light can, through a complex series of reactions, produce harmful concentrations of the ground-level ozone. The resulting air pollution is known as photochemical smog.

Particulate Matter (PM) - Particles formed by incomplete combustion of fuel. Compression ignition (diesel) engines generate significantly higher PM emissions than spark ignited engines. The particles are composed of elemental carbon, heavy hydrocarbons (SOF), and hydrated sulfuric acid (“sulfate particulates”).

Polycyclic Organic Matter (POM) - A class of air toxics defined in the U.S. Clean Air Act (CAA) as compounds with more than one benzene ring and a boiling point of 100°C and higher. Includes practically all of diesel Polynuclear aromatic hydrocarbon material.

Polynuclear Aromatic Hydrocarbons (PAH) - Aromatic hydrocarbons with two or more (up to five or six) benzene rings joined in various, more or less clustered forms.

Precombustion Chamber - A small, auxiliary combustion chamber connected by a narrow orifice with the main chamber. Fuel is injected into the prechamber and ignites there, causing hot gases to expand into the main chamber (cylinder).

Selective Catalytic Reduction (SCR) - Term frequently used as a synonym for catalytic reduction of NOx in diesel exhaust or flue gases by nitrogen containing compounds, such as ammonia or urea. Such systems are commercially available for stationary applications. Since “selective catalytic reduction” is a generic term also used in regards to other reactions, its use may lead to confusion in some situations.

Soluble Organic Fraction (SOF) - The organic fraction of diesel particulates. SOF includes heavy hydrocarbons derived from the fuel and from the engine lubricating oil. The term “soluble” originates from the analytical method used to measure SOF that is based on extraction of particulate matter samples using organic solvents.

TNRCC – Texas Natural Resource Conservation Commission

Total Carbon (TC) - The sum of the elemental carbon and organic carbon associated with diesel particulates. Typically amounts to 80-85 percent of the total DPM mass.

Turbocharging - A process of compressing the engine intake air charge in order to allow more air and fuel into the cylinder and, thus, to increase the engine power output. The compressor, called the turbocharger, is driven by an exhaust gas propelled turbine.

Volatile Organic Compounds (VOC) - Hydrocarbon-based emissions released through evaporation or combustion. The term VOC is usually used in regard to stationary emission sources.

Volatile Organic Fraction (VOF) - The organic fraction of diesel particulate matter as determined by vacuum evaporation. It may or may not be equivalent to the SOF fraction. Depending on the exact analytical procedure, the VOF may include the organic material (SOF) as well as some of the sulfate particulates which, being composed primarily of hydrated sulfuric acid, are also volatile.